ASSESSMENT OF FINE RECYCLED AGGREGATES IN MORTAR

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Abstract

In this study, the influence of fine recycled concrete aggregates as replacement for sand in mortar and the use as cement replacement and filler is investigated. Mortar with fine recycled aggregates is examined on its mechanical and physical properties. The samples are also examined on a microscopic scale. The fine recycled concrete aggregates are made with one-year old concrete made in the laboratory. Fine recycled aggregates (FRCA) are added as a cement replacement (0 %, 10 % and 20 %), as a sand replacement replacing different fractions of natural sand, and as a filler (5 %, 10 % and 25 %). For the cement replacement and filler, the fines are made as fine as possible: (< 0,32 and < 0,16 mm). Fine recycled concrete aggregates used as a cement replacement have a negative influence on all properties. For the use as a sand replacement, the mixtures show an increase in strength, but a significant decrease in workability. The use as a filler is proven feasible for mix proportion using up to 10 % of fine recycled concrete aggregates. This has a positive influence on the properties of mortar.

Keywords: *Fine recycled concrete aggregates, Mortars, Microstructure, Recycling*

1 Introduction

1.1 Fine recycled concrete aggregates as substitute for sand

A lot of construction and demolition waste (C&DW) is generated each year. In 2014 in Flanders (Belgium) about 14 million tons C&DW are generated while in China this was about 600 to 800 million tons [1] [2]. Since landfilling of C&DW has been banned in Flanders, recycling has become an important part in the sustainable development of the construction industry. C&DW, especially concrete rubble, can be recycled as aggregates in recycled concrete [3] [4] [5]. Coarse recycled concrete aggregates (CRCA) of size > 4 mm, can be used as replacement for natural aggregates according to the Standard NBN EN12620: “Aggregates for Concrete, 2013”. Due to uncertainties fine recycled concrete aggregates (FRCA) of size ≤ 4 mm cannot be used, according to this standard. As a result FRCA, representing 1/3th of the recycled aggregates, disappears in applications with no added value and recycling companies get stuck with a large amount of FRCA unless a suitable and technical sound application can be proven. This study investigates the technical possibility of using fine recycled concrete aggregates in mortar.

The availability of sand seems endless, however, the excavation of sand from the riverbed or from the seabed can lead to more erosion and environmental problems. It is estimated that 40 to 50 billion tons of sand are excavated every year [6], being worth a 70 billion dollar industry worldwide. Globally, it is the world's most excavated natural material, being 68 % to 85 % of the global mining of materials [7]. Several countries, such as China, have banned the export of sand [7] to protect their coastlines and sea life, and to protect against landslides and flooding [8] [9]. Because of several booming megacities, tons of sand are needed for the building industry. However, not all sand is suitable to make concrete. Desert sand is too fine and too smooth to give the desirable strength properties as required for concrete.

An option is to use FRCA to replace sand. This is the most convenient use for the FRCA. If used like this, FRCA will function as a part of the mortar structure. Although there is some un-hydrated cement present in the FRCA, the binding capacity of this un-hydrated cement is neglected here. Some properties of mortar, such as workability, density, water absorption, mechanical properties, will be affected when using FRCA as a sand replacement.

1.2 Fine recycled concrete aggregates as cement replacement

The production of Portland cement is an energy-intensive industry and is responsible for about 5 % of the global anthropogenic carbon dioxide emissions worldwide [10]. In 2011, the annual global cement production had reached 2,8 billion tons [11]. It is expected to grow 0,8–1,2 % per year, reaching between 3700 and 4400 megatons in 2050. This is an increase of 73–72 % since 2006 [12]. The cement consumption in China is almost half of the world production of cement and it is expected to be at its highest between 2015 and 2030 [12].

Since FRCA contains some un-hydrated old cement, FRCA can be added to mortar mix proportions as a replacement of cement. In order to do so there should be enough un-hydrated cement present in the FRCA. In this investigation, one year old laboratory concrete was crushed into FRCA. Further, the FRCA was grinded into powder so that the un-hydrated cement can be released as cement and hydrate in the new mortar. The replacement of cement with FRCA will lead to a decrease of the strength, since not all particles are un-hydrated and are not reacting.

1.3 Fine recycled concrete aggregates as a filler

The third option for FRCA is the use as a filler in mortar mixtures. This option may have the best potential for application. Compared to the use of FRCA as sand or cement replacement which leads to decrease of mechanical properties, using FRCA as a filler may result in an increase of mechanical properties. The function of the FRCA might be dual. The FRCA consists of both sand and cement properties and consists mostly out of SiO2 and CaO [13].The un-hydrated cement particles will join the water-cement reaction and increase the strength. The other particles will, when grinded into filler, fill up the cavities in the mortar. This can result in an increase of strength.

1.4 Properties of Fine Recycled Concrete Aggregates

In general it can be expected that the properties of FRCA will be lower when compared to natural aggregates. This is due to the attached mortar on the aggregates which is the main reason of the lower quality of recycled aggregates, which in turn can lead to a decline of the mechanical properties of concrete and mortar when recycled aggregates are used [14]. The water absorption of FRCA is an important factor since it influences the water demand of the mortar of concrete mixture. The average value for FRCA of size 0 – 4 mm is (9,9 ± 2,2) %. The age of the original concrete from which FRCA was derived is not important [15].

To determine the density of an aggregate, a distinction must be made between the apparent density ρ_a , the dry-oven density ρ_{rd} and the saturated surface dry density ρ_{ssd}. Many studies use the dry-oven density ρ_{rd}, others the saturated surface dry density ρ_{ssd}. These densities can be determined according to the standard NBN EN 1097-6: *Tests for mechanical and physical properties of aggregates – Part 6: Determination of particle density and water. 2006*. The average value for the saturated surface dry density ρ_{ssd} of FRCA 0–4 mm is (2,28 ± 1,1) g/cm³.

2 Experimental program

2.1 Experimental materials

The constituents for the mortar mixtures are basically cement, sand and water. When assessing the possible use of FRCA as sand replacement, it is important to know the particle size distribution of the natural sand. In the experiments with sand replacement, the several fractions are replaced according to the particle size distribution of the natural sand. The fraction 0–0,16 mm and 0,16–0,32 mm are considered together as a fraction 0–0,32 mm. Table 1.

Tab. 1 *Sand fractions to be replaced in mortar with FRCA as sand replacement*

Particle size distribution of natural sand		**Replacement by FRCA**
Fraction min – max [mm]	*Amount [%]*	*Mass [kg]*
0 – 0,16	3,78	1,297
0,16 – 0,32	28,24	
0,32 – 0,63	24,05	0,974
0,63 – 1,25	21,24	0,860
1,25 – 2,50	11,44	0,463
2,50 – 5,00	11,25	0,456
sum	*100*	*4,050*

2.2 Mix Proportions

The mortar mixtures were made with a fixed cement/sand-ratio of 1/3 $_{M/M}$. The control mortar mixtures were made with 1,35 kg cement and 4,05 kg sand. The replaced sand fractions are noted in table 1. Three different W/C-ratios (0,55–0,6–0,65) were used for the experiments. FRCA was used as sand replacement, as filler and as cement replacement. The replacement of cement by FRCA was done with fractions 0–0,16mm and 0–0,32 mm, with respectively 0, 10 and 20 %. The use of FCRS as a filler was investigated with fractions 0–0,16 mm and 0–0,32 mm for respectively 0, 5, 10 and 25 % added filler. Ordinary Portland cement CEM I-32,5 was used in the experiments. Following notation is used for the mixtures with FRCA as sand replacement: W/C-ratio+SR+fraction. Example: 0,65SR1,25 stand for W/C-ratio 0,66 , sand replacement fraction 0–1,25 mm. In total 18 different mortar mixtures were made to study the sand replacement. The notation for cement replacement by FRCA is as follows: W/C-ratio+CR+%+fraction. Example: 0,55CR200,16 stands for a mortar mix with W/C- ratio 0,55, 10 % cement replacement by FRCA of fraction 0–0,16 mm. If ‘P’ is added to the notation, then additional plasticizer was added. The notation for the mortar mixtures with FRCA as a filler is: W/C-ratio+Filler%+used fraction. Example: 0,6F5S0,3 stands for W/C-ratio 0,6 , 5 % filler and FRCA fraction 0–0,32 mm.

2.3 Experiments

A series of experiments was selected to assess the use of FRCA in mortar mixtures: the consistency of the fresh mortar, the dry density of hardened mortar, the water absorption of hardened mortar, the flexural and compressive strength. And finally a microanalysis was done on hardened mortar using a Scanning Electron Microscope (SEM).

The consistency of mortar was determined by measuring the resistance again the intrusion of a cone of diameter 75 mm, height 150 mm and weight 300 g, in the fresh mortar. This test is performed according to the *Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry, ASTM C780-14*.

The dry density of hardened mortar was determined according to the Standard NBN EN 1015-10: *Methods of test for mortar for masonry – Part 10: Determination of dry bulk density of hardened mortar (1999)*.

The water absorption of hardened mortar was measured according to the Standard NBN EN B15-215: *Water absorption by complete submersion (1999)*.

The flexural and compressive strength of mortar prisms size 160 x 40 x 40 mm³ was determined according to the Standard NBN EN 1015-11: *Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar. (1999)*. This was done at 7, 14 and 28 days of age.

3 Results and discussion

3.1 Consistency of fresh mortar

As expected, the workability and consistency of fresh mortar decreased when sand was replaced by FRCA. The higher the replacement rate, the higher the decline in workability. The drop in workability was higher when using coarser fractions of FRCA in the mortar mixture. The addition of the finest fractions FRCA as a filler to the mortar mixture also resulted in a decrease of workability as can be seen in Figure 1.

3.2 Dry density of hardened mortar

The dry density of mortar in which sand was replaced by FRCA decreases slightly when using fractions less than 0,63 mm. When using fractions of more than 0,63 mm then the decrease was not noticed. This is probably because the coarser fractions are less different from natural sand since they contain more sand and less attached mortar. The density of mortar in which cement was replaced by the finest fractions of FRCA (0–0,16 and 0–0,32 mm), decreases with an increasing amount of replacement. The density of the mortar made with 0–0,16 mm FRCA as cement replacement resulted in higher densities compared to the use of FRCA fraction 0–0,32 mm. The dry density of hardened mortar made with FRCA as filler added to the mixture increases with an increasing amount of filler added. For mixtures where 25 % filler 0–0,16 mm was added, the increase in dry density was 13,27 %. Figure 2.

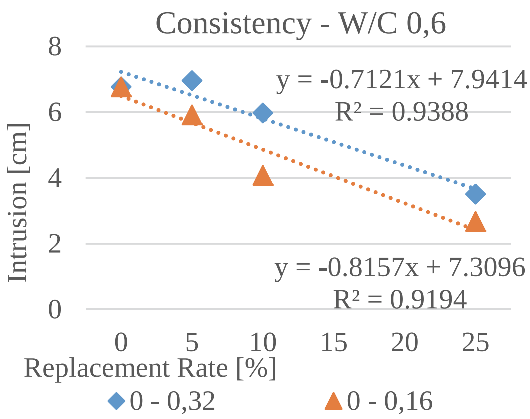

Fig. 1 *Consistency of fresh mortar using 0 – 5 – 10 – 25% FRCA fraction 0-0,16 mm and 0-0,32 mm as filler in mortar*

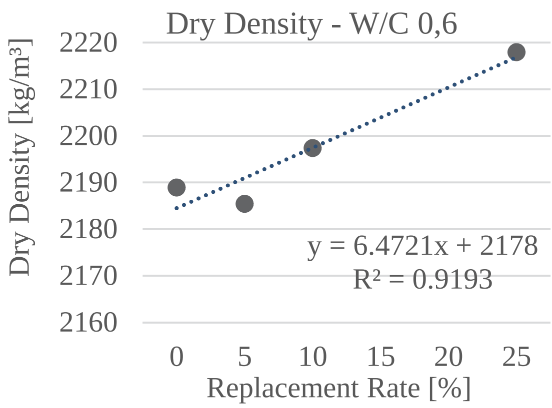

Fig. 2 *Dry density of hardened mortar using 0 – 5 – 10 – 25% FRCA fraction 0-0,16 mm as filler in mortar*

3.3 Water absorption [16]of hardened mortar

The water absorption of hardened mortar (WA) increased with an increasing replacement rate of sand by FRCA. For mortar with 100 % replacement of sand by FRCA this was 6,88 %. The WA also increased for hardened mortar made with replacement of cement with FRCA. 20 % replacement of cement with FRCA 0–0,32 mm resulted in an increase of 11,36 %, and replacing 20 % cement with FRCA 0–0,16 mm gave an increase of the water absorption with 16,92 %. The WA of hardened mortar with 10 % FRCA filler 0–0,16 mm added, decreased with 8,27 % compared to the reference control mixture.

3.4 Flexural and compressive strength of hardened mortar

When using FRCA an increase of the flexural strength is noticed. This is caused by the presence of un-hydrated cement particles in the FRCA. Other researchers also came to this conclusion. [16] The largest part of the increase occurs in the first couple of days. The strength development is higher between the seventh and the fourteenth day compared to that of the control mixtures without FRCA. Later-on the strength development is similar to that of the control mixtures. Figure 4. At 28 days of age the increase of flexural strength of samples with 100 % substitution of sand by FRCA is 37,74 % compared to the control mixture. The increase is the highest for the mixtures replacing only the fraction 0–0,32 mm and W/C-ratio 0,55. When also replacing the coarser fractions of FRCA, then the difference between the flexural strength becomes smaller. This suggests that the influence on the flexural strength is the highest when replacing the filler part or fines of the sand by the same fraction of FRCA. For other W/C-ratio’s a similar trend in increase of flexural strength was noted.

When using the finest fractions of FRCA as a replacement for cement, the flexural strength development is lower compared to the control mixture. This is because in these fractions of FRCA only a part of them are un-hydrated cement particles while other particles are hydrated cement particles and fines of natural aggregates. The latter don’t participate in the cementing actions of the mortar. In total, the W/C-ratio (or better Water/Binder-ratio) is less when compared to the control mixture and so a decrease of flexural strength can be expected. When replacing cement with 10 % FRCA fraction 0–0,16 mm and W/C-ratio 0,55 , the decrease in flexural strength is the least and equals 7,47 %. The highest decrease of 26,98 % was noted when replacing cement with 20 % FRCA fraction 0–0,32 mm.

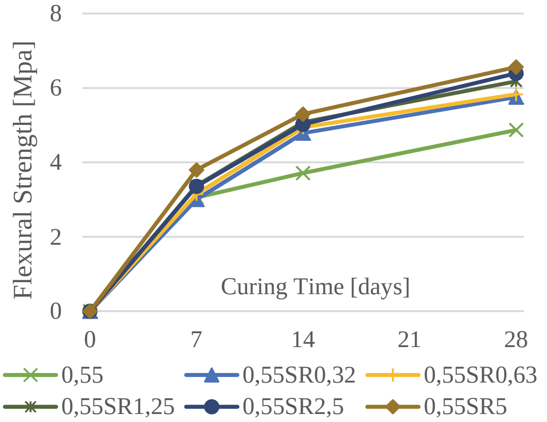

Fig. 3 *Flexural strength development of mortar with 100% replacement of sand by FRCA in several fractions and W/C-ratio 0,55*

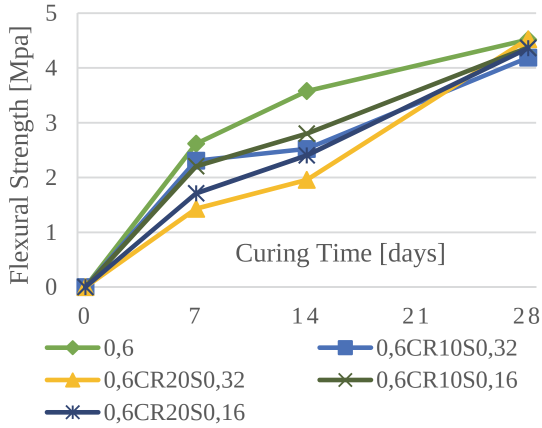

Fig. 4 *Flexural strength development of mortar with cement replacement by FRCA at W/C-ratio 0,6*

The addition of filler to the mortar mixture proves to be beneficial for the flexural strength. The strength is the highest when adding FRCA fraction 0–0,16 mm. When adding 25 % filler FRCA 0–0,32 mm and FRCA 0–0,16 mm to the mortar mixture with W/C 0,6 , an increase of flexural strength of 17,63 % and respectively 23,78 % is found. Figure 5.

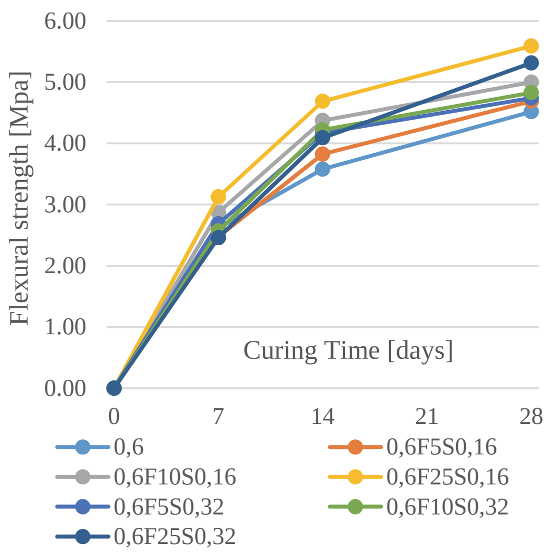

Fig. 5 *Flexural strength development of mortar with added FRCA- filler in several fractions and W/C-ratio 0,55*

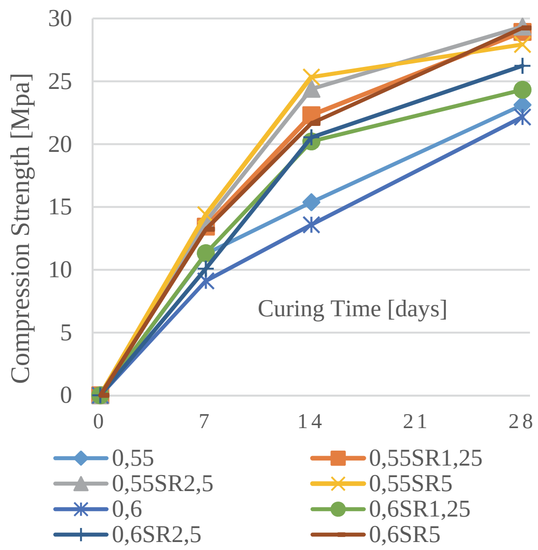

Fig. 6 *Compressive strength development of mortar with sand replacement by FRCA W/C-ratio 0,55 & 0,6*

Similar results as for the flexural strength are found for the compressive strength. An increase in strength is found when replacing the larger of sand by the equivalent fraction of FRCA. 100 % replacement gives the best result. An increase of 20,88 % and 31,97 % was reached with 100 % replacement of sand in mortar with W/C-ratio respectively 0,55 and 0,60. Fig. 6.

Mortar made with cement replacement by FRCA fractions 0–0,16 and 0–0,32 mm decreases in strength. The largest decrease when replacing 20 % cement with FRCA 0–0,32 mm at W/C-ratio 0,55 is 11,93 %, at W/C-ratio 0,66 this is 21,41 % . When using 20 % FRCA 0–0,16 mm the decrease is 16,45 %.

The compression strength increases when adding a filler fraction FRCA. When adding 25 % FRCA 0–0,16 mm and respectively 0–0,32 mm in mortar with W/C-ratio 0,6 , then the increase in compression strength is 31,99 %, respectively 14,84 %.

3.5 SEM analysis

Mortar samples were tested with the SEM microscope. At x2000 times magnification some clear components can be distinguished: (A) Natural sand, (B) Cement paste (C-S-H), this is the main component of the cement hydration, (C) Ettringite, these 'needles' are hydration products of calcium aluminate, (D) Monosulphate, these plate-shaped structures are also a hydration product of calcium aluminate, (E) Cavities. Figure 7.

Figure 8 shows a SEM image of mortar with 100 % sand replacement by FRCA. Weak ITZ zones (red lines in figure 9) can lead to cracks more easily. They are always situated next to aggregates and are due to the attached mortar.

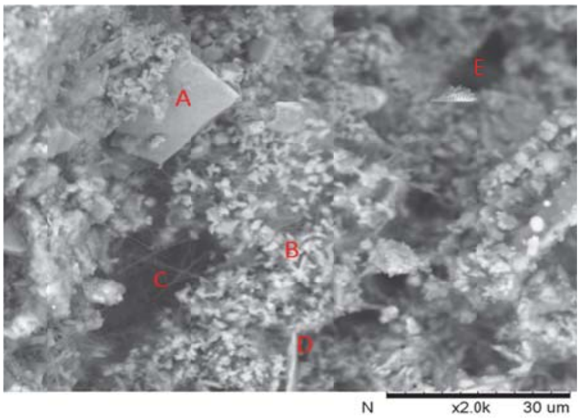

Fig. 7 *SEM image of components in mortar (A) Natural sand, (B) Cement paste, (C) Ettringite, (D) Monosulphate, (E) Cavities*

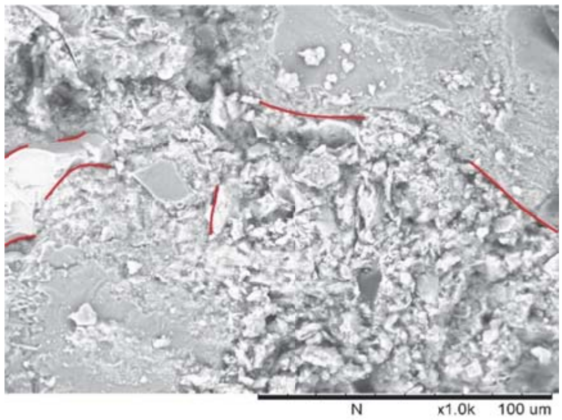

Fig. 8 *SEM image of ITZ in mortar with 100% replacement of sand by FRCA*

4 Conclusion

From this investigation can be concluded that Fine Recycled Concrete Aggregates have good potentials for use in mortars to replace sand. Although the workability declines, the mechanical properties increase. The fractions 0–0,16 and 0–0,32 mm can be added to mortar as a filler. Both the flexural and compression strength increase. Also the water absorption by immersion is less when using fillers. However, the mechanical properties decrease when used to replace cement.

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